FACULTY OF TECHNOLOGY

Deployment of small modular reactors: Finnish perspective

Henna Möttönen

PROCESS AND ENVIRONMENTAL ENGINEERING

Bachelor's thesis

December 2020

TIIVISTELMÄ

Pienten modulaaristen reaktoreiden käyttöönotto Suomessa

Henna Möttönen

Oulun yliopisto, prosessi- ja ympäristötekniikan tutkinto-ohjelma

Kandidaatintyö 2020, 31 s.

Työn ohjaaja yliopistolla: Antonio Caló

Tämän kandidaatintyön aiheena ovat pienet modulaariset ydinreaktorit (SMR). Tavoitteena on selvittää, millaisia SMR-konsepteja on olemassa sekä mitä etuja ja haasteita pienillä reaktoreilla on. Erityisesti työssä keskitytään lisensointiprosessin haasteisiin ja siihen, miten Suomen lainsäädäntöä voidaan soveltaa SMR-voimaloihin. Työssä tarkastellaan lyhyesti myös ydinvoimaloiden päätoimintaperiaatteita sekä ydinjätteen loppusijoitusta Suomessa. Työ on tyypiltään kirjallisuuskatsaus.

SMR-voimaloita voidaan käyttää sähkön, kaukolämmön ja teollisuuslämmön tuottamiseen. Ne tarjoavat mahdollisuuden siirtyä keskitetyistä sähköntuotantokeskuksista hajautettuihin keskuksiin, mikä parantaisi sähköverkon toimitusvarmuutta. SMR:t hyödyntävät passiivisia turvallisuusjärjestelmiä ja ovat rakenteeltaan yksinkertaisempia kuin suuret ydinvoimalat. SMR-voimaloita voitaisiin mahdollisesti valmistaa sarjatuotantona, mikä laskisi niiden kustannuksia.

Suurin osa SMR-voimaloista on kuitenkin vasta suunnitteluasteella, ja niitä on rakennettu vain muutamia koko maailmassa. Näin ollen varmuutta niiden hinnasta ja kilpailukyvystä perinteisten reaktoreiden kanssa ei ole. Lisensointi on SMR-voimaloille haaste, sillä Suomen nykyinen lainsäädäntö on tehty suurille kevytvesireaktoreille eikä sitä voida suoraan soveltaa SMR-voimaloihin. SMR-voimaloiden tuottama ydinjäte on samanlaista kuin suurten ydinvoimaloiden, joten niiden käsittelyyn ja loppusijoitukseen voitaisiin käyttää samanlaisia menetelmiä. Tällä hetkellä loppusijoitus kallioperään on todennäköisin vaihtoehto.

Asiasanat: pieni modulaarinen ydinreaktori, SMR, lisensointi, reaktorityypit

ABSTRACT

Deployment of small modular reactors: Finnish perspective

Henna Möttönen

University of Oulu, Process and Environmental Engineering

Bachelor's thesis 2020, 31 pp.

Supervisor at the university: Antonio Caló

The topic of this bachelor's thesis is small modular reactors (SMRs). Different SMR concepts are introduced in the thesis. Competitive advantages and challenges are presented as well. The work focuses on the license procedure and how Finnish legislation can be applied to SMRs. The fundamentals of nuclear power plants and the final disposal of nuclear waste are discussed briefly. The thesis is conducted as a literature review.

SMRs can be used to generate electricity, district heat, and industrial heat. They offer an opportunity to move from centralized power plants to decentralized ones which would improve the grid stability. SMRs utilize passive safety systems and therefore are simpler than traditional, large nuclear power plants. Serial production could reduce the costs of SMRs.

However, most SMRs are still in the designing phase and only few have been constructed worldwide. Therefore, it cannot be said with certainty if SMRs are competitive with conventional reactors. Licensing is seen as the greatest challenge for SMRs, because current Finnish legislation is made for large light water reactors and is not strictly applicable to SMRs.

The nuclear waste generated by SMRs is similar to the waste large reactors produce, so same treatment and disposal methods could be used for both. Currently disposal in the bedrock is most likely option to be carried out in Finland.

Keywords: small modular reactors, SMR, reactor concepts, license procedure, Finnish nuclear legislation

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ATHR	Advanced High Temperature Reactor
BWR	Boiling-Water Reactor
FNR	Fast Neutron Reactor
GWd/t	gigawatt-days (thermal) per tonne
HTR	High-Temperature Gas-cooled Reactor
IAEA	International Atomic Energy Agency
kWe	kilowatt-electric
LFR	Lead-cooled Fast Reactor
LWR	Light Water Reactor
MSFR	Molten Salt Fast Neutron Reactor
MSR	Molten Salt Reactor
MWe	megawatt electrical
O&M	Operation and Maintenance
PWR	Pressurized-Water Reactor
R&D	Research and Development
SFR	Sodium-cooled Fast Reactor
SMR	Small Modular Reactor
STUK	The Radiation and Nuclear Safety Authority
WENRA	Western European Nuclear Regulators Association

1 INTRODUCTION

Presently one the most considerable global challenges is transitioning to more sustainable energy production. That means shifting from nonrenewable energy sources to clean energy sources, such as wind, hydro and solar. (U.S. Energy Information Administration, 2020a) Fossil fuels are still the world's primary energy source even though the share of renewable energy is rising. In 2015 approximately 80 % of the total energy consumed in the world was produced by utilizing fossil fuels (The World Bank, 2020).

Burning fossil fuels causes a huge amount of CO_2 emissions. Carbon dioxide is one of the main greenhouse gases that are responsible for the greenhouse effect and acceleration of global warming. Because almost 80% of the energy in the world is currently produced by fossil fuels, shutting down fossil fuel power plants would create a significant challenge for the global energy system. The fossil fuel plants are expected to be replaced with more environmentally friendly power plants utilizing renewable energy sources. (U.S. Energy Information Administration, 2020a)

Nuclear energy may have a part in this transitioning to more sustainable energy. Currently nuclear energy covers up approximately 10% of the world energy production (World Nuclear Association, 2020a). In Finland, the share of nuclear energy in total energy consumption was 26,6 % in 2019 (Official Statistics of Finland (OSF), 2020). New reactor designs are developed to solve the issues conventional nuclear power plants have. SMRs are small, under 300 MWe nuclear power reactors that can be used for both electricity and heat production. The main reasons why SMRs have drawn much attention are simpler design, possibility of serial production and shorter construction time when compared with large nuclear power plants. However, licensing and new technology utilized are challenges for SMR deployment. (World Nuclear Association 2020b)

This bachelor's thesis aims to present an overview of SMRs. Different designs, challenges and advantages SMRs have, are discussed. The thesis focuses especially on challenges relating license procedures in Finland. In addition to the topics mentioned above, nuclear waste disposal and fundamentals of nuclear power plants are introduced briefly. Since this is a bachelor's thesis, the purpose is not to evaluate all the details but to give an overall picture of SMRs.

2 FUNDAMENTALS OF A NUCLEAR POWER PLANT

Nuclear power plants are thermal power stations that exploit fission reactions to create heat. Heat is used to generate steam which drives turbines. The turbines are connected to an alternator which converts mechanical energy into electricity. Excluding fission, a basic principle of generating electricity is similar to other power plants - such as fossil fuel stations. (The French Alternative Energies & Atomic Energy Commission, 2016) Components of a nuclear power plant are discussed more precisely in the following sections.

2.1 Fission

In nuclear fission neutrons collide with an atomic nucleus. The nucleus is charged positively, whereas neutrons do not have an electric charge. Therefore, there is no repulsive force, and neutrons can get close to the nucleus. When neutrons collide with the nucleus, it splits into two parts. These fission products are often unstable, and they ultimately decay into other more stable elements. Unstable elements are radioactive, which means they emit radiation during the decay. (The French Alternative Energies & Atomic Energy Commission, 2016)

In addition to the unstable nuclei, each fission reaction generally produces two or three high-energy neutrons. These neutrons collide with other nuclei and start new fission reactions generating a chain reaction. The velocity of fission products is approximately 8000 km/s. When they collide with other atoms, the sudden and significant loss of kinetic energy transforms into heat. This heat is used to generate electricity. (The French Alternative Energies & Atomic Energy Commission, 2016)

2.2 Nuclear fuel and waste

Uranium-235 is the most commonly utilized nuclear fuel. Natural uranium consists of isotopes U-235 (0.7 %), U-238 (99.3 %) and a trace amount of U-234. (U.S. Nuclear Regulatory Commission, 2020) Most nuclear reactor types use enriched uranium as a fuel. In the enrichment process, the proportion of the U-235 is increased from 0.7 % to 3.5 - 5.0 %. Using natural uranium to run a nuclear reactor is also possible. In this case, instead of ordinary water, there has to be graphite or heavy water as a moderator. (World Nuclear Association, 2020c) Moderators are discussed more precisely in section 2.3.

Enriched uranium oxide is used to run most reactors. Enriched uranium is compressed into ceramic fuel pellets which are approximately 1.5 cm in lenght and 1 cm in diameter. Pellets are loaded into a 4 m long rods made of zirconium alloy. Zirconium is used due to its corrosion resistance, hardness, and neutron transparency. Fuel rods are then bundled as in the figure 1 below and inserted into a reactor core. (World Nuclear Association, 2020c)

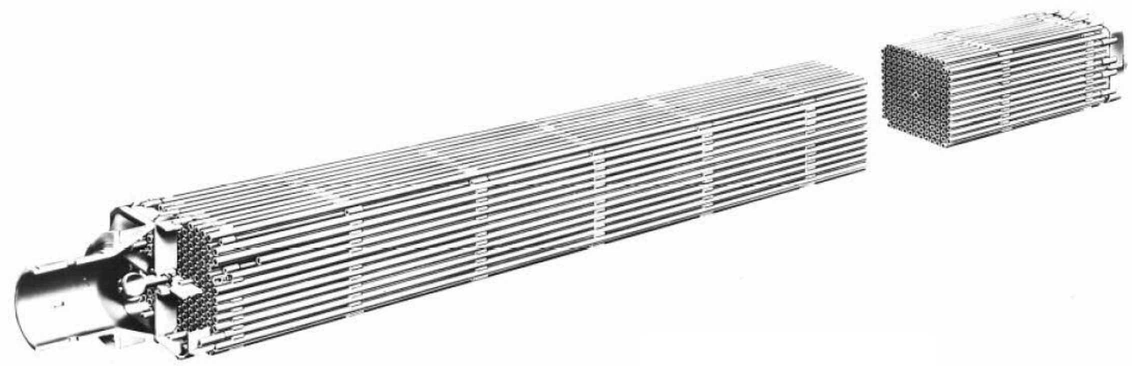


Figure 1. A fuel bundle (also referred as a fuel assembly) of a pressurized water reactor containing four bundles of 41 fuel rods (U.S. Maritime Administration, 1961).

Most reactors need to be shut down for refueling. The reactor vessel is then opened, and approximately a third of the fuel assemblies are replaced with new ones. Refueling interval depends on fuel burn-up. Fuel burn-up measures what amount of energy is extracted from a certain quantity of fuel. The unit is usually gigawatt-days (thermal) per tonne (GWd/t). Fuel burn-up is related to fuel enrichment. Up to the present time, a limit for burn-up level has been 40 GWd/t with 4 % fuel enrichment. Fuel assemblies have not been robust enough to withstand higher burn-up levels, but currently 55 GWd/t is achievable with 5 % enrichment and advanced fuel assemblies. With 6 % enrichment, it is possible to reach 70 GWd/t. Higher burn-up would increase refueling interval from 12 to 18 months up to 24 months and lower fuel cycle costs by 20 %. (World Nuclear Association, 2020d)

Producing electricity or heat using a nuclear power plant generates radioactive waste. The unstable nuclei produced in fission emit radiation and slowly decay into non-radioactive, stable substances. Based on the radioactivity left in the nuclear waste, it can be divided into low, intermediate-, and high-level waste. Low- and intermediate-level wastes are also referred to as reactor waste. Low-level waste is generated during the operation and maintenance work when the objects such as tools and protective clothing have been in contact with radioactive materials and therefore have been contaminated. (Posiva Oy Olkiluoto, 2010) Intermediate-level waste is also generated during the O&M. For example, filters and steel components used in the reactor are intermediate-level waste. High-level waste consists of spent nuclear fuel. The high-level waste covers 3 % of the total volume of nuclear waste, and it contains 95 % of the radioactivity. Low-level waste covers 90 % of the total volume of nuclear waste, but it contains only 1 % of the total radioactivity. 7 % of the nuclear waste is intermediate-level waste containing 4 % of the total radioactivity. (World Nuclear Association, 2020e) In addition to reactor waste and spent nuclear fuel, decommissioning a nuclear power plant generates waste. Decommissioning means dismantling the power plant at the end of its life cycle. (Posiva Oy Olkiluoto, 2010)

Spent high-level nuclear fuel emits both radiation and heat, so it needs to be loaded into a storage pool after being removed from a reactor. The water in the pool acts as a shield and absorbs radiation and decay heat. The water of the pool is circulated through heat exchangers, and heat is recovered. Spent fuel is held in storage pools until radiation levels decrease. Within a year the radiation levels have decreased to one-hundredth of the levels measured immediately after removing spent fuel from the reactor. Eventually, used fuel is either reprocessed and recycled or put in long-term storage and disposed. (World Nuclear Association, 2020d; Posiva Oy Olkiluoto, 2010)

2.3 Control systems

Control rods are used to manage the fission rate. They are made of materials which absorb neutrons, such as boron, cadmium, or hafnium. As neutrons are absorbed by the rods, there are fewer collisions with nuclei and fission rate decreases. The rods can be inserted or withdrawn from the reactor core. Withdrawing increases and inserting decreases the fission rate. (World Nuclear Association, 2020c; The French Alternative Energies & Atomic Energy Commission, 2016)

Moderator is required in most reactors to decrease the velocity of high-energy neutrons. The initial velocity of the neutrons is approximately 20,000 km/s and it needs to be decelerated to 2 km/s, otherwise neutrons have an excessive amount of energy and the chain reaction does not occur properly. Neutrons are slowed down by directing them to matter consisted of light nuclei. Unlike fissile nuclei, light nuclei do not split up when colliding with neutrons. (World Nuclear Association, 2020c; The French Alternative Energies & Atomic Energy Commission, 2016)

Water is generally used as a moderator. Ordinary water is not efficient enough to moderate reactors powered by natural uranium. These reactors require heavy water or graphite for moderator. Heavy water contains deuterium atoms whereas light water (the term is used to differentiate heavy water from ordinary water) contains hydrogen. Deuterium is an isotope of hydrogen. Deuterium absorbs fewer neutrons compared to hydrogen, which makes heavy water more efficient moderator. (World Nuclear Association, 2020d)

Coolant is used to transfer heat from the core to components generating electricity, such as a turbine. Common coolants are water, lead, sodium, helium, and carbon dioxide. Coolant varies depending on the reactor type. The functional cooling system is essential, otherwise the temperature of the core increases uncontrollably and reactor core melts. (The French Alternative Energies & Atomic Energy Commission, 2016)

3 SMR DESIGNS

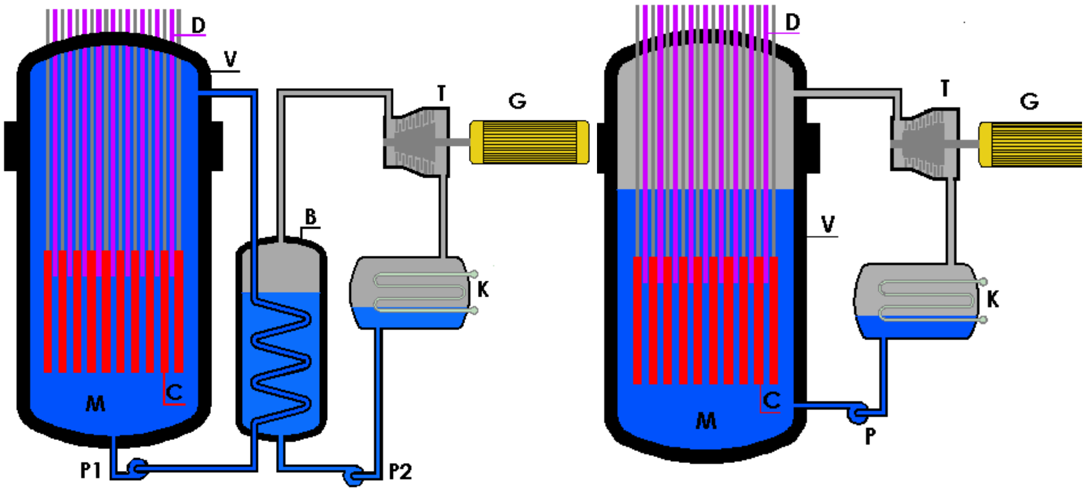
The World Nuclear Association defines SMRs as under 300 MWe reactors, but the International Atomic Energy Agency (IAEA) refers both small and medium (under 700 MWe) reactors as SMRs. As a comparison, conventional reactor units can be over 1600 MWe. However, commonly abbreviation "SMR" is used when discussed small modular reactors. It should be noted that small reactors are being constructed, yet they are not modular reactors. (World Nuclear Association 2020b) In this paper, SMRs are defined as under 300 MWe reactors which are factory manufactured and assembled of modules at a site.

Numerous SMR designs have been made globally. Most of the designs are still in the developmental stage. The leading countries in SMR development are China, the United States, and Russia. Several countries, including Finland, have shown their interests in taking part in the research. Presently SMR designing focuses mostly on four reactor types: light water reactors, fast neutron reactors, graphite-moderated high-temperature reactors, and molten salt reactors. (World Nuclear Association 2020b) These reactor concepts are presented in following sections.

3.1 Light water reactors

Light water reactors (LWRs) are the most common reactor types, so the technology is well-known and technological risks are lower if compared to rarely used reactor types. Concerning SMR development, LWRs are the most promising reactor type. LWRs are divided into two groups: **pressurized-water reactors (PWR)** and **boiling-water reactors (BWR)**. (Spinrad and Marcum, 2019)

PWRs have primary and secondary water loops. The primary loop water streams through the core and acts as a coolant. The heat from the core is transferred to the primary water loop where the water does not boil due to high pressure. Heat is conducted from the primary water loop to a secondary, low-pressure water loop via a heat exchanger. The secondary loop water enters the steam generator where superheated water evaporates, and generated steam is directed to the turbine. In contrast to PWRs, boiling-water reactors have one water loop instead of two. The water begins to boil as it streams through the core. Due to that, there is no need for steam generators. The generated steam is separated from the water with steam separators and directed to the steam turbine. (Spinrad and Marcum, 2019) Schematics of PWR (on the left) and BWR are introduced below (Figure 2).



a) b)

Figure 2. Schematics of PWR (a) and BWR (b). The components: B. steam generator (only in PWR), C. fuel rods, D. control rods, G. generator, K. steam condenser, M. reactor, P1/P. primary pump, P2. secondary pump (only in PWR), T. turbine, and V. pressure vessel. (from Castelnuovo, 2005a; Castelnuovo, 2005b)

In BWR design, the steam cycle is simpler than in PWR, but the emergency-system for core-cooling and the vessel's internal components are more complex. Because BWRs have only one water loop, heat loss between the core and the turbine is lower. However, BWRs have lower power density and they require larger pressure vessel to reach the same reactor power PWRs have. (Spinrad and Marcum, 2019)

One example of the small PWRs is a Russian KLT-40S reactor developed by OKBM Afrikantov. The unit produces 35 MWe and additionally 35 MW of heat. The refueling interval is 3-4 years and operational lifetime is approximately 40 years. Russian Akademik Lomonosov, the first floating nuclear power plant, has two KLT-40S units and it has been operating since 2019. OKBM Afrikantov has also designed RITM-200M reactor that is optimized for floating nuclear power plants. It produces 50 MWe and the operating lifetime is up to 60 years. KLTs are expected to be replaced with RITM-200M units at some point. (World Nuclear Association, 2020b)

3.2 Fast neutron reactors

If compared to light water reactors, fast neutron reactors (FNRs) are smaller and have a simpler design. FNRs do not have moderators, unlike LWRs and traditional reactors where the water is used as a neutron moderator. As a coolant FNRs use liquid metals, for example lead and sodium. Fuels used are enriched to 15-20 % and the refueling interval is longer, up to 20 years. The operating pressure is at atmospheric pressure or near that. (World Nuclear Association 2020b)

Sodium-cooled fast reactors (SFRs) use sodium as a coolant. Sodium reacts rapidly with water and it is also flammable. Lead or lead-bismuth used in **lead-cooled fast reactors (LFR)** does not react either with water or air. LFRs do not require as comprehensive safety systems for coolant leakage protection as SFRs do, so they have lower costs to construct. However, lead and lead-bismuth are corrosive metals which has to be taken into account in designing. (World Nuclear Association 2020b)

Even though PWRs are the most common currently operating nuclear reactors, generation IV designs are mostly FNRs. Generation IV means six reactor technologies that are believed to be the future of nuclear power. All these designs focus especially on sustainability, safety and minimizing wastes. Only two of these are slow neutron reactors (as currently operating ones) and the rest are FNRs. Some of these Generation IV types may be in operation by 2030 but not until a new safety case is made at least in western countries. (World Nuclear Association 2020c)

3.3 Graphite-moderated high-temperature reactors

High-temperature gas-cooled reactors (HTR) use graphite as a moderator. Helium is the most used primary coolant, but also nitrogen and carbon dioxide can be used. During the last decades, the technology has developed and new HTRs are more efficient than previous ones. They can reach a temperature of 700-950 °C and be used both steam generating and industrial applications. (World Nuclear Association 2020b)

HTR fuel consists of small pebbles that have a uranium oxycarbide core. The core is covered by carbon layers and silicon carbide. If compared to the same capacity LWR, HTR produces 20 times more used fuel in volume because over 99% of the fuel pebbles consist of graphite. Because of higher burning temperature, the used fuel releases less decay heat and it is not as radioactive. Thorium-based fuels have been experienced in HTRs. HTRs are relatively small reactors, so they could be factory-built and then transported to the desired location. When it comes to safety, rising temperature inherently slows down the fission reaction. Decay heat also removes passively. Due to these, HTRs do not require comprehensive safety mechanisms. (World Nuclear Association 2020b)

3.4 Molten salt reactors

Molten salt reactors (MSRs) are cooled with molten fluoride salts, such as lithium and lithium-beryllium fluoride salts (FLiBe). Operating pressure is near atmospheric pressure (atm) which decreases the risk of explosion and release of radioactive material to the environment. If compared to PWRs which operate in approximately 315 °C and 150 atm, MSRs operate in 700 °C. It is possible to reach higher temperatures however it has not been experimented to date. Due to high temperatures, MSRs could potentially be used for process heat. (World Nuclear Association, 2020b)

Fuel used in conventional MSRs is a mixture of enriched uranium dissolved in the coolant. Lithium used in the salt mixture is generally pure Li-7 which is expensive to enrich. Fuel cycle of MSR has many attractive opportunities. Dissolved fission products can be removed from the fuel salt and replaced with uranium (or thorium) in an online reprocessing loop. The waste MSRs produce is high-level nuclear waste which requires shorter-term interim storage. High operating temperature increases thermal efficiency, and less fuel is needed due to higher burn-up. (World Nuclear Association, 2018)

To date, there have not been operational MSRs since 1960s. However, numerous designs are being developed internationally. Currently the Generation IV program for the MSR focuses on two concepts: **Molten Salt Fast Neutron Reactor (MSFR)** and **Advanced High-Temperature Reactor (AHTR)**. As a liquid-fuel design, MSFR could possibly use thorium as a fuel. They would produce a minimum amount of waste, require less fuel, and operate more safely. AHTR has less potential for thorium-based fuel use due to solid-fuel design. If compared to conventional HTR, ATHR has 4 to 6 times higher power density. Currently MSFR and ATHR concepts are at viability research and development phase (R&D) which is expected to be finished by 2025. (World Nuclear Association, 2018)

4 BENEFITS AND CHALLENGES

Compared to large reactors, small modular reactors offer many attractive characteristics. Many fossil fuel power plants are ageing around the world and SMRs are one choice for replacing them. Multiple small units instead of a single large one increases grid stability. SMRs would be especially useful for remote locations. SMRs have simplified design, a possibility for serial production, and lower siting costs. They offer lower financial risk for investors which would lead to private sector funded nuclear research and development instead of current, government-led R&D. Some designs could be built underground or -water which reduces the risk of terrorist attacks and natural hazards. SMRs have potential for countries with little experience of nuclear energy due to passive safety features and simplified design. SMRs have other applications in addition to generating electricity, such as process heat and district heat production. (World Nuclear Association, 2020b)

However, there are multiple challenges to overcome before deployment. There are only estimates of SMR cost and therefore further analyses are needed to determine if SMRs are economically competitive with large reactors. Transporting of spent nuclear fuel from remotely located reactors is difficult and it needs to be carefully planned. If SMRs are used for district heating, they have to be built near the cities which may provoke public opposition. (Vujić et al., 2012) VTT Technical Research Centre of Finland has started developing SMR for district heating. Since the carbon dioxide emissions caused by district heat production were over four million tonnes in 2019, fossil fuels used in heat production need to be replaced with low-emission energy source, for example with nuclear energy. SMRs and nuclear energy are also proposed to be an alternative for coal-fired power plants, of which Finland has decided to give up by 2029. SMRs for district heating would be more simple and possibly more economic than SMRs intended for industrial applications or electricity production. (VTT Technical Research Centre of Finland, 2020) Current licensing systems for nuclear facilities are optimized for large reactors and they vary from one country to another. Differences in national safety requirements complicate serial production because manufacturers have to tailor reactors for every project and country. (Radiation and Nuclear Safety Authority, 2019) Licensing aspects are discussed more precisely in chapter “Legal framework on Small Modular Reactors”.

The economy of scale principle is widely accepted in the nuclear industry and due to that the reactor size has increased for the past decades. The economy of scale states that increasing size and power supply of a reactor decrease the specific capital cost. Currency per KWe is often used as a unit of the specific capital cost. According to the economy of scale, high performance and larger equipment increase the power output (kWe) relatively more than set-up costs. The set-up costs consist of licensing, construction and connecting the power plant to transmission network for example. The economy of scale principle applies when two technically similar reactors are being compared. However, SMRs are not necessarily smaller versions of large reactors but a new concept using different technical characteristics. Therefore, most SMRs and large reactors are too dissimilar for the economy of scale being directly applicable. (Locatelli et al., 2014)

To reduce the size of a nuclear reactor, technical solutions and compromises are required. One of these solutions is to rely on natural circulation in an integral vessel, which contains primary components such as heat exchangers. Natural circulation is not possible to implement in large reactors which use pumps to circulate fluids. Due to passive safety, SMRs do not usually require as comprehensive safety systems as large reactors do and therefore fewer components are needed. This reduces reactor size and decreases costs. Most SMR designs are yet in R&D stage and proposed new technical characteristics have to be experimented before commercialization. (Locatelli et al., 2014)

Nuclear power plant life cycle costs consist of investment cost, operating and maintenance, fuel, and decommissioning. Levelised Unit Electricity Cost (or Levelised Cost Of Electricity) is one of the most important indicators when estimating costs. LUEC or LCOE is a ratio between the life cycle costs and produced electrical energy ($/kWh). (Locatelli et al., 2014) According to Carelli et al. (2010), the capital cost of four 335 MWe SMRs is 5 % higher than one 1340 MWe large reactor. However, Nuclear Energy Agency (2011) states that the specific capital cost of SMR may be up to hundreds of percents higher than the specific capital cost of a large reactor. NEA’s calculation is based on the economy of scale principle. (Nuclear Energy Agency, 2011) When total investment costs are defined, other SMR characteristics have to be taken into account. SMRs are factory-assembled and require less on-site fabrication than large reactors which shortens the construction time. Shorter construction time reduces the specific capital cost up to 20% and factory manufacturing up to 40% depending on the amount of fieldwork required. If the overall capacity of the site is not limited, it is cheaper to build multiple reactors on existing site because the set-up activities, such as transmission networks, are already done. Building multiple SMR units reduces the specific capital cost by 10-25% (per unit). As mentioned before, the simplified design is a competitive advantage for SMRs over large reactors. It is estimated that the specific capital cost reduction for pressurized water SMR – which is seen as the most potential type for near-term deployment – would be 15% or more. (Nuclear Energy Agency, 2011, p. 15; Locatelli et al., 2014)

Operation and maintenance costs are considered as the most significant life cycle cost after the capital cost. O&M costs consist of labor, material, and other costs. It is concluded that four 335 MWe SMRs have 24 % higher O&M cost than one 1430 MWe large reactor. This calculation does not take into account the technical advantages SMRs have. Therefore, the difference between O&M costs is expected to be smaller. (Locatelli et al., 2014)

5 LEGAL FRAMEWORK ON SMRS

Licensing is often seen as the most significant challenge for SMRs. Use of nuclear energy is strictly regulated in Finland because in case of an accident, damages for people, environment and property can be severe. In current nuclear legislation different size reactors are not distinguished, but the regulations can be applied more easily for large light water reactors. For some parts SMR and large reactor construction projects differ substantially which makes applying the law difficult. For example, a single facility may have several small reactors built at different times instead of one large reactor. Also staggered reactor construction and non-traditional smaller power companies may complicate the license procedure. The license procedure of SMRs would take significantly longer time of total construction duration than large reactor license procedure. Therefore, legislative changes are needed to ease the licensing process. In 2019, the Ministry of Economic Affairs and Employment of Finland started a legislative project for developing the Nuclear Energy Act. (Ahonen et al., 2019)

The license procedure consists of applying for decision-in-principle, construction license, operation license and decommissioning license. The Parliament votes on if the decision-in-principle is approved or rejected. The licenses are granted by the Government. STUK assess the fulfilment of safety requirements in all license phases and grants approval for construction and decommissioning. The safety assessments have to be considered by the Government when deciding if the licenses are granted. (Ahonen et al., 2019) Characteristics of each license phases are briefly introduced in the following sections. Regulations relating to safety arrangements, safeguards of nuclear materials, and nuclear waste management are discussed later in this chapter.

5.1 Decision-in-principle and license procedure

According to Section 11 of the Nuclear Energy Act, the first phase of the license procedure is a Government decision-in-principle. In decision-in-principle it is determined whether constructing a nuclear facility is in accordance with the overall good of society. The Ministry of the Environment, a municipality where facility is intended to locate, and neighbouring municipalities submit statements for the Ministry of Economic Affairs and Employment (former Ministry of Trade and Industry). Ministry of Economic Affairs and

Employment also obtains a preliminary safety assessment from STUK. These documents are included in an application which is submitted to the Government. When considering the decision-in-principle, the Government pays attention especially to three issues: is there a need for the nuclear facility concerning Finland's energy supply, is the intended site suitable for the nuclear facility and how it effects to the environment, and how nuclear fuel and waste management is arranged. If the Government judges that constructing the nuclear facility is in accordance with the overall good of society, a decision-in-principle is forwarded to the Parliament for perusal. The Parliament either approves the decision-in-principle as it is or rejects it. (990/1987, §12-§15) However, decision-in-principle is not required for nuclear facilities having a thermal power less than 50 megawatts (990/1987, §11). Therefore, the license procedure for under 50 MW SMRs would be easier than over 50 MW SMRs. Current legislation allows the applicant/licensee to apply a decision-in-principle for several reactors or sites at the time. However, it is a standard practice to grant permission for only one reactor or site at the time. (Ahonen et al., 2019)

The second phase of the license procedure is applying for a construction license. The construction license application is addressed to the Government and the following information have to be included: the applicant's or firm name, the location of the site, operating principle of the facility, expected service life, power range, the schedule of construction and a decision-in-principle (when it is required). A number of detailed information about the applicant have to be included, such as an outline of the operating organization, applicant's plan for nuclear waste management and a description of the expertise of applicant and organization. (161/1988, §31 & §32) When applying for a construction license, the applicant has to submit a preliminary safety analysis report and other plans for ensuring nuclear safety to STUK (161/1988, §35).

After the construction license has been granted, the operating license is applied. As with the construction license, operating license application is addressed to the Government. Information about the safety principles, the financial status of the applicant, and technical operating principles for example have to be included in the application. Also information about complying provisions of the construction license and possible previous operating licenses have to be included. (161/1988, §33 & §34) The operating license is granted for a fixed term, but the length of the term is not specified in legislation. Especially estimated operating period and safety ensuring plans affect the length of the term. The operating license has to be renewed at the end of the term. (990/1987, §24)

At the end of the life cycle of the nuclear facility, the licensee has to apply for a decommissioning license. Decommissioning license application is addressed to the Government. It can be noted that similar information is required in all construction, operating and decommissioning license applications. The following information have to be included to the decommissioning application: the name of the applicant/firm, location of the site, previous use of the nuclear facility, planned implementation schedule for decommissioning, and previous operating license. (161/1988, §33a) In addition to the information about the applicant, descriptions of technical principles, environmental impact, and nuclear waste management at the decommissioning phase for example are required (161/1988, §34a). The license applicant also shall submit a final decommissioning plan and other information about the safety of decommissioning process for STUK (161/1988, §36a). The Ministry of Economic Affairs and Employment obtains statements from The Ministry of the Environment, a municipality where facility is intended to locate, and neighbouring municipalities before the license is granted by the Government (161/1988, §37).

5.2 Safety arrangements

According to the Nuclear Energy Act, the use of nuclear energy shall not cause any danger or damage for people, environment, or property (990/1987, §6). Requirements concerning nuclear safety are defined in chapter 2a of Nuclear Energy Act (990/1987). The chapter includes measures for ensuring safety in construction, operation and decommissioning as well as in operational occurrences and accidents. More detailed safety requirements are made by STUK (990/1987, §7r).

As required by the Act, STUK has prepared Regulatory Guides on Nuclear Safety and security (YVL). The Guides are divided into five groups, which are: Safety management of a nuclear facility (A), Plant and system design (B), Radiation safety of a nuclear facility and environment (C), Nuclear materials and waste (D), and Structures and equipment of a nuclear facility (E). Safety requirements concerning the site of a nuclear facility are defined in Guide YVL A.2. (The Radiation and Nuclear Safety Authority, 2020b) In addition to the Guides, safety requirements and emergency arrangements are also discussed in Regulation on the Emergency Arrangements of a Nuclear Power Plant (The Radiation and Nuclear Safety Authority, 2018).

The regulation states that only operations related to nuclear power are allowed at the site. The licensee has an authority to make the site area only available for certain personnel, and limit staying at the site. This site area covers from 0.5 to 1 kilometer from the plant. The nuclear facility is surrounded by the precautionary action zone and the emergency planning zone. The precautionary action zone covers 5 kilometers radius from the plant and land-use restrictions have been set at the area. Hospitals, schools, factories, and other facilities where number of people visit, and which are hard to evacuate in the case of emergency, are not permitted in the area. Limited permanent residence and recreational housing are allowed at the area, but a plan for evacuation has to be made for the area. The emergency planning zone covers 20 kilometers radius from the plant. Authorities are required to draw a detailed external rescue plan for this area. It should be noted that the precautionary action zone is included to the emergency planning zone. (The Radiation and Nuclear Safety Authority, 2019)

The regulations and restrictions mentioned above have been made for large nuclear power reactors. Especially for SMRs utilized for district heating or industrial use, the land-use restrictions prescribed by law are problematic. If SMR is used for district heat production, it should be located near the city and according to the current legislation it is not possible. The sizes of the precautionary action zone and the emergency planning zone should be redefined in a way they would take into account a reactor size. It is often assessed that SMRs could be located closer to cities and significant facilities than large reactors because SMRs exploit passive safety systems. Due to reduced reactor size, an individual SMR also contains less radioactive materials than a large reactor does. However, if multiple SMRs are built at the same site and severe operational occurrence happens simultaneously in several reactors, the impact of the accidents may be equivalent to an accident of a large reactor. (Ahonen et al, 2019)

5.3 Safeguards of nuclear materials

Safeguards of nuclear materials aim to secure use of nuclear materials, such as nuclear fuel. They ensure that nuclear materials are not used for nuclear weapons or other purposes prohibited by law. The control system of nuclear materials is maintained by STUK. STUK also monitors that the licensee has the necessary expertise to organize the supervision and the supervision is implemented by the licensee in accordance with the regulations. (161/1988, §118) In addition to STUK, the European Atomic Energy

Community and IAEA supervise the peaceful use of nuclear energy (990/1987, §63). The licensee appoints person/persons responsible for safeguards of nuclear materials and security arrangements. These persons are accepted by STUK (990/1987, §7i). The safeguards for current Finnish nuclear power plants can be applied for water-cooled SMRs. Monitoring and seals for nuclear fuel containers, for instance, could be used to prevent unauthorized access to nuclear fuel. SMRs would have special safety requirements and arrangements for fuel transports, which increase due to decentralized locations. (Ahonen al, 2019)

In some SMR concepts only a few employees are needed in the operating stage and there are also some designs which do not require any physical presence of personnel. Controlling these unmanned reactors would be remote and one control room could supervise multiple reactors. However, there are many issues concerning remote controlling. Technical maintenance of an unmanned reactor requires new procedures - for example robotics have been proposed – but these have not been experimented in nuclear facilities yet. Delay and response time have to be taken into account in monitoring and especially in security systems. Remote controlling also complicates supervising the implementation of nuclear material safeguards. (Ahonen et al., 2019)

5.4 Nuclear waste management

In Nuclear Energy Act, nuclear waste is referred as a) radioactive waste in the form of spent fuel or other form generated as a result of the use of nuclear energy, or b) substances, objects and structures of a nuclear power plant which have become radioactive and require special measures after decommissioning (990/1987, §3). The licensee of a nuclear facility is responsible for nuclear waste management (990/1987, §9). Low- and intermediate-level wastes are usually short-term stored at the site. It is expected that SMRs are constructed by smaller power companies than conventional large nuclear power plants. Reactors are likely built to decentralized locations which makes it impractical for each small operator to arrange their own nuclear waste management facility. Therefore, several centralized waste management arrangements have been proposed. Nuclear wastes of SMRs could be managed in cooperation with large nuclear power operators and Posiva. (Ahonen et al., 2019) Posiva is an organization which prepares the final disposal of nuclear waste for its owners, Teollisuuden Voima Oyj and Fortum Power and Heat (Posiva Oy Olkiluoto, 2010). The second option is that all SMR licensees would arrange the waste management together. The third option is to establish a national nuclear waste management company. (Ahonen et al., 2019) It should be noted that the licensee is accountable for the costs in all these alternatives mentioned above (990/1987, §9).

If the reactor module is fueled in a factory and then transported to the site, there is no need for a short-term storage at the site. In this case, the module containing used nuclear fuel could be treated at a separate processing plant after decommissioning. There is not the kind of facility in Finland yet. (Ahonen et al., 2019) Nuclear Energy Act states transporting nuclear waste with low levels of radioactive material abroad for treatment in an appropriate manner is permitted. After processing, the wastes have to be returned to Finland for final disposal. However, legislative changes are required to enable transporting modules containing higher levels of radioactive material abroad for processing, or a processing plant needs to be built in Finland. (990/1987, §6a; Ahonen et al., 2019)

5.5 International cooperation for harmonization of license procedures

License procedures for nuclear power plants vary between countries. Especially national safety requirements differ from each other. Therefore, instead of serial production, SMRs have to be tailored for each country which causes decrease in profitability. Common safety requirement base and harmonized license procedures would benefit licensing and safety authorities as well as nuclear industry. If national requirements would be similar, preparation of safety assessments can be made in cooperation with several countries. However, some national differences will likely remain in any case. (Ahonen et al., 2019)

The IAEA and Western European Nuclear Regulators Association (WENRA) are the most important international organizations which have started a process for harmonization of license procedures. Member countries of IAEA collaborate to draw up safety standards. WENRA has developed Safety Objectives for new large light water reactors under construction. Safety Reference Levels developed also by WENRA are applied for operating power plants. Both IAEA's and WENRA's objectives are made with large light water reactors in mind and are not strictly applicable for SMRs. In 2019 WENRA started an evaluation of applying safety requirements for SMRs. STUK is involved in this evaluation. In addition to work of IAEA and WENRA, SMR Regulator's

Forum takes part in developing the license procedures. The forum focuses on defining and solving the challenges of license procedures and safety requirements instead of trying to harmonize the requirements. STUK is also involved in this forum. (Ahonen et al., 2019)

6 FINAL DISPOSAL OF NUCLEAR WASTE

Finland is said to have one of the world's most advanced plan for spent nuclear fuel repository and final disposal. In 1995, Posiva Oy was set up by Fortum Power and Heat Oy and Teollisuuden Voima Oyj. The company prepares to implement the final disposal of nuclear waste generated by its owners. According to the studies made by Posiva and the Swedish nuclear waste company SKB, the bedrock of Olkiluoto in Eurajoki is stable enough for safe nuclear waste disposal. The excavation of final disposal tunnels, ONKALO, started there in 2004. Tunnels extend to a depth of approximately 400 meters.

As mentioned in chapter five, cooperation with Posiva could be one option for SMR nuclear waste management and final disposal. Conventional large reactors and small modular reactors, which use the same type of fuel, generate similar waste. One waste treatment process can be applied for both. After radiation levels have reduced enough during the interim storage, reactor waste is intended to be transferred to an aboveground encapsulation plant. The safety of final disposal is ensured by the multibarrier principle. As discussed before, the fuel assemblies typically consist of fuel pellets which are stacked and assembled into zirconium rods. The fuel assemblies are then packed into canisters in the encapsulation plant. Inside of the canister is coated with nodular graphite cast iron which protects the fuel assemblies from mechanical strain, for example earthquakes. Canister overpack is made of copper, which is corrosion resistant and protects the canister from groundwater. The canisters are put into holes, which are drilled into tunnel floors. The holes are then filled with bentonite clay and canisters are isolated from the bedrock by bentonite. Bentonite absorbs the groundwater and prevents water from getting contact with the canisters. After canisters are placed, the tunnels are filled to prevent water from accessing the canisters and moving them. In addition to other safety ensuring measures, hundreds of meters bedrock protect the canisters from terrestrial changes. (Posiva Oy Olkiluoto, 2010)

It is important to note that final disposal has not been implemented yet in anywhere in the world. Finland plans to begin the final disposal in the middle 2020s. Then Finland would be the first country in the world to implement final disposal. (The Radiation and Nuclear Safety Authority, 2020a)

7 CONCLUSIONS

Energy production is clearly shifting away from old, polluting fossil-based energy towards renewable, clean energy. Since nuclear power plants do not produce carbon dioxide emissions when operating, SMRs may have a role in transitioning this low-carbon energy system. Because demand for energy is increasing, having reliable electricity grids is essential. SMRs are planned to be built apart from each other which would improve grid stability especially in remote areas. Currently power plants are highly centralized and electricity power transmission networks are hundreds of kilometers long. If fault occurs in the transmission line or other parts of the distribution system, it can lead to power outage. With decentralized SMRs the effects of a fault would be less severe, and the outage would affect to smaller number of end users.

SMRs offer many attractive features but also challenges to overcome. Licensing is seen as the most significant challenge for SMR deployment. Current regulations are made for large reactors and are not strictly applicable for SMRs. It also has to be noted that most SMR designs are in developmental stage and exist only on paper. Only few are under construction or operating. New technology utilized in some SMR designs, for example in FNRs, has to be researched and experimented carefully. Because SMRs are not commercialized yet, there are only estimates of the costs. It is widely believed that serial production would reduce the price of reactors. Profitable serial production would require somewhat harmonized national license procedures which do not exist yet. Therefore, it is not known with certainty if SMRs are competitive with large reactors.

As current license procedures are made for light water reactors with well-known technology, the first SMRs to deploy are probably LWR-types. Especially SMRs intended for district heating have aroused interest in Finnish municipalities. However, locating these SMRs near the cities may arouse public opposition. The timetable for commissioning first SMRs mainly depends on when legislative changes will be made to ease the license procedure. It is unlikely that there would be SMRs operating before 2030.

REFERENCES

Ahonen et al., 2019. Preconditions for safe use of small modular reactors – outlook for the licensing system and regulatory control [online]. Helsinki: Radiation and Nuclear Safety Authority. Available from: http://urn.fi/URN:ISBN:978-952-309-454-3.

Carelli, et al., 2010. Economic features of integral, modular, small-to-medium size reactors. *Progress in Nuclear Energy* [online], 52 (4), (403-414). Available from: https://doi.org/10.1016/j.pnucene.2009.09.003

Castelnuovo, 2005a. Schematic of a Boiling Water Nuclear Reactor [online]. Available from: https://commons.wikimedia.org/wiki/File:BWR1.png [Accessed 10.12.2020].

Castelnuovo, 2005b. Schematic of a PWR nuclear reactor [online]. Available from: https://commons.wikimedia.org/wiki/File:PWR1.png [Accessed 10.12.2020].

Locatelli et al., 2014. Small modular reactors: A comprehensive overview of their economics and strategic aspects. *Progress in Nuclear Energy* [online], vol. 73, 75-85. Available from: https://doi.org/10.1016/j.pnucene.2014.01.010

Nuclear Energy Act (990/1987). Available from: https://finlex.fi/en/laki/kaannokset/1987/en19870990

Nuclear Energy Agency, 2011. *Current Status, Technological Feasibility and Economics of Small Nuclear Reactors* [online]. France: Nuclear Energy Agency / Organisation for Economic Co-operation and Development (OECD). Available from: https://www.oecd-nea.org/ndd/reports/2011/current-status-small-reactors.pdf

Nuclear Energy Decree (161/1988). Available from: https://finlex.fi/en/laki/kaannokset/1988/en19880161

Official Statistics of Finland (OSF), 2020. *Energia: Sähkön hankinta ja kokonaiskulutus* [online]. Helsinki: Statistics Finland. Available from: https://www.stat.fi/tup/suoluk/suoluk_energia.html [Accessed 17.9.2020].

Posiva Oy Olkiluoto, 2010. *Safe Final Disposal of Spent Nuclear Fuel* [online]. Eurajoki: Posiva Oy. Available from: http://www.posiva.fi/files/1233/Posiva_final_disposal_en.pdf [Accessed 5.12.2020].

Radiation and Nuclear Safety Authority, 2020a. *Finland to submit notification of final disposal to countries supplying uranium fuel* [online]. Helsinki: The Radiation and Nuclear Safety Authority. Available from: https://www.sttinfo.fi/tiedote/finland-to-submit-notification-of-final-disposal-to-countries-supplying-uranium-fuel?publisherId=64456131&releaseId=69893183 [Accessed 6.12.2020].

Radiation and Nuclear Safety Authority, 2018. *STUK Y/2/2018: Radiation and Nuclear Safety Authority Regulation on the Emergency Arrangements of a Nuclear Power Plant* [online]. Helsinki: The Radiation and Nuclear Safety Authority. Available from: https://www.stuklex.fi/en/maarays/stuk-y-2-2018

Radiation and Nuclear Safety Authority, 2020b. *STUK Y/2/2018: Regulatory Guides on nuclear safety (YVL)* [online]. Helsinki: The Radiation and Nuclear Safety Authority. Available from: https://www.stuklex.fi/en/yvl-ohje

Radiation and Nuclear Safety Authority, 2019. *YVL A.2: Site for a nuclear facility, 15.2.2019* [online]. Helsinki: The Radiation and Nuclear Safety Authority. Available from: https://www.stuklex.fi/en/ohje/YVLA-2

Spinrad and Marcum, 2019. *Nuclear reactor* [online]. United States: Encyclopædia Britannica, inc. Available from: https://www.britannica.com/technology/nuclear-reactor/Types-of-reactors#ref155185 [Accessed 20.9.2020].

The French Alternative Energies & Atomic Energy Commission, 2016. *Nuclear reactors* [online]. Gif-sur-Yvette Cedex: France. Available from: https://www.cea.fr/english/Documents/thematic-publications/cea-nuclear-reactors.pdf [Accessed 8.10.2020].

The World Bank, 2020. *Fossil fuel energy consumption (% of total)* [online]. Washington DC: The World Bank. Available from: https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS [Accessed 16.9.2020].

U.S. Energy Information Administration, 2020a. *Energy and the environment explained: Where greenhouse gases come from* [online]. Washington DC: U. S. Energy Information Administration. Available from: https://www.eia.gov/energyexplained/energy-and-the-environment/where-greenhouse-gases-come-from.php [Accessed 16.9.2020].

U.S. Maritime Administration, 1961. A nuclear fuel element for the cargo ship NS Savannah [online]. Available from: https://maritime.org/tour/savannah/press/techpicts.htm [Accessed 10.12.2020].

U.S. Nuclear Regulatory Commission, 2020. *Natural uranium* [online]. Washington DC: U.S Nuclear Regulatory Commission. Available from: https://www.nrc.gov/about-nrc/contactus.html [Accessed 8.10.2020].

VTT Technical Research Centre of Finland, 2020. *Good riddance to fossil fuels! VTT develops a Small Modular Reactor for district heating* [online]. Espoo: VTT Technical Research Centre of Finland. Available from: https://www.vttresearch.com/en/news-and-ideas/good-riddance-fossil-fuels-vtt-develops-small-modular-reactor-district-heating [Accessed 18.9.2020].

Vujić, et al., 2012. Small modular reactors: Simpler, safer, cheaper? *Energy* [online], 45(1), 288-295. Available from: https://doi.org/10.1016/j.energy.2012.01.078

World Nuclear Association, 2020a. *Nuclear Power in the World Today* [online]. United Kingdom: World Nuclear Association. Available from: https://www.world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx [Accessed 17.9.2020].

World Nuclear Association, 2020b. *Small nuclear power reactors* [online]. United Kingdom: World Nuclear Association. Available from: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx [Accessed 15.11.2020].

World Nuclear Association, 2020c. *Nuclear Power Reactors* [online]. United Kingdom: World Nuclear Association. Available from: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx [Accessed 8.10.2020].

World Nuclear Association, 2020d. *Nuclear Fuel Cycle Overview* [online]. United Kingdom: World Nuclear Association. Available from: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/nuclear-fuel-cycle-overview.aspx [Accessed 8.10.2020].

World Nuclear Association, 2020e. *What is nuclear waste, and what do we do with it?* [online]. United Kingdom: World Nuclear Association. Available from: https://www.world-nuclear.org/nuclear-essentials/what-is-nuclear-waste-and-what-do-we-do-with-it.aspx [Accessed 5.12.2020].

World Nuclear Association, 2018. *Molten Salt Reactors* [online]. United Kingdom: World Nuclear Association. Available from: https://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx [Accessed 29.10.2020].